Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 5 February 2008 (MN LATEX style file v2.2)

Carbon-Rich Mira Variables: Kinematics and Absolute Magnitudes

Michael W. Feast[1⋆], Patricia A. Whitelock[1,2,3], John W. Menzies[2]
[1] *Astronomy Dept. University of Cape Town, Rondebosch, 7701, South Africa*
[2] *South African Astronomical Observatory, P.O. Box 9, Observatory, 7935, South Africa*
[3] *National Astrophysics and Space Science Programme, University of Cape Town, Rondebosch 7701, South Africa*

5 February 2008

ABSTRACT
The kinematics of galactic C-Miras are discussed on the basis of the bolometric magnitudes and radial velocities of Papers I and II of this series. Differential galactic rotation is used to derive a zero-point for the bolometric period-luminosity relation which is in satisfactory agreement with that inferred from the LMC C-Miras. We find for the galactic Miras, $M_{bol} = -2.54 logP + 2.06(\pm 0.24)$, where the slope is taken from the LMC. The mean velocity dispersion, together with the data of Nordström et al. and the Padova models, leads to a mean age for our sample of C-Miras of 1.8 ± 0.4 Gyr and a mean initial mass of 1.8 ± 0.2 $M_{\odot}$. Evidence for a variation of velocity dispersion with period is found, indicating a dependence of period on age and initial mass, the longer period stars being younger. We discuss the relation between the O- and C-Miras and also their relative numbers in different systems.

Key words: Stars: AGB and post-AGB - stars: carbon - stars: distances - stars: Variable: other - Galaxy: kinematics and dynamics - Galaxy: fundamental parameters - stars: individual: V CrB, ZZ Gem, KY Cam, AZ Aur, RT Gem, IRAS 06088+1909, IRAS 16171-4759, IRAS 17222-2328.

1 INTRODUCTION

This is the third and last of a group of papers dealing with the properties of carbon-rich Mira variables. In this paper we combine the photometry and bolometric data of Whitelock et al. (2006, Paper I) and the radial velocities listed in Menzies et al. (2006, Paper II) to discuss the kinematics of the C-Miras. A main aim of this paper is to derive estimates of the absolute magnitudes, ages and initial masses of galactic C-Miras. These parameters are of importance both for understanding the place of C-Miras in stellar evolution and for using them as probes of the stellar populations in other galaxies. Whilst there have been some estimates of the likely mass range of carbon stars in general (e.g. from studies of their galactic distribution (Claussen et al. 1987, Groenewegen et al. 1995), and considerable theoretical work on the production of carbon stars, there has been little or no observational evidence on the ages and masses of C-Miras except for the occurrence of three of them in intermediate age clusters in the Magellanic Clouds (Nishida et al. 2000) and one of somewhat uncertain period in another LMC cluster (van Loon et al. 2003), but see also the discussion on IRAS 04496–6958 in section 6. There has been no evidence as to whether or not ages and initial masses of C-Miras vary with period. As regards the luminosities of galactic C-Miras, Whitelock & Feast (2000) found that a satisfactory zero-point for the PL(K) relation could not be obtained from Hipparcos parallaxes due mainly to the small number with significant weight. Other estimates of C-Mira luminosities were discussed in paper I.

2 ANALYSIS

The radial velocities used in this analysis are those listed in table 4 of Paper II where they have been corrected to our adopted local standard of rest. The local solar motion adopted was: $u_{\circ} = +9.3\,\mathrm{km\,s^{-1}}$ (towards the galactic centre), $v_{\circ} = +11.2\,\mathrm{km\,s^{-1}}$ (in the direction of galactic rotation), and $w_{\circ} = +7.6\,\mathrm{km\,s^{-1}}$ (towards the north galactic pole). These are the values derived by Feast & Whitelock (1997) (see also Feast 2000).

Heliocentric distances were obtained using the period-luminosity relation derived from LMC observations of C-Miras in Paper I, viz.,

⋆ e-mail: mwf@artemisia.ast.uct.ac.za

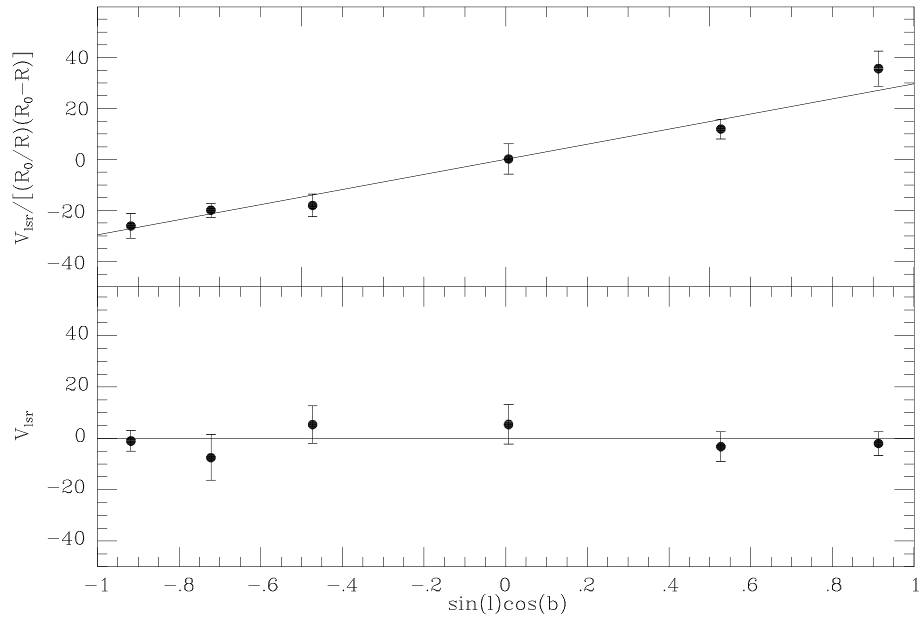

Figure 1. (a). Weighted mean value of $V_{lsr}/[(R_\circ/R)(R_\circ - R)]$ plotted against $\sin\ell\cos b$. The line has a slope of $2A = 29.6\,\mathrm{km\,s^{-1}kpc^{-1}}$ (b). V_{lsr} plotted against $\sin\ell\cos b$.

$$M_{bol} = -2.54\log P + c. \quad (1)$$

For an assumed LMC distance modulus of 18.50 the constant term in this equation was found to be $c = 1.87$. Distances using this value were tabulated in Paper II (their table 4). One aim of the present analysis is to estimate the value of c for the galactic sample. The standard general relation for differential galactic rotation used in the analysis was

$$V_{lsr} = 2A(R_\circ/R)(R_\circ - R)\sin\ell\cos b + U_\circ\cos\ell\cos b + V_\circ\sin\ell\cos b + W_\circ\sin b + K \quad (2)$$

where:

- V_{lsr} is the radial velocity relative to the local standard of rest (lsr),
- A is Oort's constant of differential galactic rotation,
- $R_\circ$ is the distance from the Sun to the Galactic Centre,
- R is the distance of the Mira from the galactic axis of rotation (i.e. cylindrical rotation is assumed),
- ℓ and b are the galactic longitude and latitude of the Mira,
- $U_\circ$, $V_\circ$ and $W_\circ$ are the components of any group motion with respect to the adopted standard of rest and in the same directions as the lsr components given above.
- The K term tests for possible systematic effects in the radial velocities.

We adopt $R_\circ = 7.62 \pm 0.32$ kpc from Eisenhauer et al. (2005). This is the value derived from the motions of objects close to the central black hole. We also adopt $A = 14.82 \pm 0.84\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ from the analysis of the Hipparcos proper motions of galactic Cepheids (Feast & Whitelock 1997). We carried out some preliminary calculations including in equation 2 some higher order rotation terms, A_2 and A_3 in the nomenclature of Pont et al. (1994), and using the values obtained for them by these workers from an analysis of Cepheid radial velocities. However, their values were not confirmed in the analysis of Cepheid proper motions (Feast & Whitelock 1997) and may be due to group motions on the kiloparsec scale which are known to occur for young objects. Group motions of Cepheids do not necessarily apply to an older population such as the C-Miras. Furthermore, since we restrict our main discussion to objects having $|R - R_\circ| \leq 2$ kpc, the effect of the higher order terms is minor.

That differential galactic rotation is clearly present in our sample can be seen from Fig. 1. Here we plot, the mean values of the quantity, $V_{lsr}/[(R_\circ/R)(R_\circ - R)]$, weighted by $[(R_\circ/R)(R_\circ - R)]^2$, against $\sin\ell\cos b$ for the stars with $|R - R_\circ| \leq 2$ kpc. For distances we have used equation 1 with $c = 1.87$ from the LMC. The points have been grouped by $\sin\ell\cos b$ so as to obtain approximately equal weights for each point. The standard errors are shown. For differential galactic rotation we expect a line of slope $2A$ as is indeed seen. Also plotted are grouped values of V_{lsr} against $\sin\ell\cos b$ which shows that there is no effect of asymmetric drift (i.e. $V_o \sim 0$ as shown below). Note that in this and subsequent work we omit the high velocity C-Mira V CrB which is discussed in section 5.

Table 1 gives the results of solving equation 2, with distances based on equation 1 and $c = 1.87$, for the 146 stars with $|R_\circ - R| < 2$kpc both with K left free and with it put to zero. The table shows that within the uncertainties U_o, V_o, W_o and K are zero and this has been assumed in the following. Also shown for comparison in Table 1 are the results using distances based on equation 1 but with the constant term (c) taken as 2.06, the value we derive later. Individual distances with this value of c are also listed in table 4 of Paper II. In Table 1, $\log P$ is the weighted mean period [1].

With $U_\circ$, $V_\circ$, $W_\circ$ and K put equal to zero we have solved

[1] The different numbers of stars in the various solutions of tables

Table 1. Preliminary Solutions

c	A	U_o	V_o	W_o	K	N	$\log P$
mag	$\mathrm{km\,s^{-1}\,kpc^{-1}}$	$\mathrm{km\,s^{-1}}$	$\mathrm{km\,s^{-1}}$	$\mathrm{km\,s^{-1}}$	$\mathrm{km\,s^{-1}}$		
1.87	13.4 ± 1.4	-1.0 ± 3.0	$+1.5 \pm 2.4$	-3.5 ± 7.1	-0.7 ± 1.8	146	2.718
1.87	13.4 ± 1.4	-1.1 ± 3.0	$+1.7 \pm 2.4$	-3.6 ± 7.0	0	146	2.718
2.06	14.8 ± 1.5	-0.7 ± 3.0	$+0.7 \pm 2.4$	-3.8 ± 7.0	-0.2 ± 1.8	149	2.717
2.06	14.8 ± 1.5	-0.7 ± 3.0	$+0.8 \pm 2.3$	-3.8 ± 7.0	0	149	2.717

equation 2 for A using a range of values of the constant term on the right hand side of equation 1. Results are shown in Table 2. For each change in the PL zero-point the interstellar absorption for each star has been iterated as described in Paper I. The number of stars in each solution is given as well as the weighted mean log period. Adopting $A = 14.82 \pm 0.84\,\mathrm{km\,s^{-1}kpc^{-1}}$ from Cepheids (Feast & Whitelock 1997) one finds for the PL zero-point,

$$c = 2.06 \pm 0.24.$$

The estimated error includes both the uncertainties in the values of A from the C-Miras and in that from Cepheids. A solution adopting $R_\circ = 8.0\,\mathrm{kpc}$ gives $c = 2.07$ indicating that uncertainty in $R_\circ$ does not significantly affect our result.

The data were subdivided by period to see whether it was possible to get an independent slope for the PL relation. However, the results were inconclusive.

The 149 stars used to derive the constant term 2.06 have a weighted mean $\log P = 2.717$. Fig. 2 shows a plot of the LMC C-Mira data discussed in Paper I with an assumed LMC modulus of 18.50 together with a point and its error bar corresponding to the galactic result. It can be seen that within the uncertainties the derived absolute magnitude does not differ significantly from that of stars of the same $\log P$ in the LMC at its adopted distance. In principle a bias correction is necessary to the galactic zero-point calculated above (see for instance Feast 2002). However, provided the true scatter of absolute bolometric magnitudes about the period-luminosity relation is as small in the Galaxy as in the LMC ($\sigma = 0.17$ mag, see Paper I), this correction is negligibly small. Numerous recent discussions (e.g. Feast 2003b) suggest that the uncertainty in the distance modulus of the LMC is 0.1mag or less. This is better than that of our galactic determination. Thus, since the two PL zero-point determinations agree within the errors we decided it was best to use the LMC calibration for the discussion of paper I. For convenience distances based on both zero-points are given for the radial velocity sample in paper II. In the present paper the galactic calibration is used in the determination of the dispersions so as to be consistent in the kinematic analysis.

3 VELOCITY DISPERSIONS, AGES AND MASSES

Using equation 1 with c= 2.06 and equation 2 with $A = 14.82$ and U_o, V_o, W_o and K put equal to zero, we calculated

1 and 2 are due to the movement of stars into or out of the $|R - R_\circ|$ annulus as a result of the changes in the adopted distance scale.

Table 2. PL Zero-Point Determination

c	A	N	$\log P$
mag	$\mathrm{km\,s^{-1}kpc^{-1}}$		
1.8	13.2 ± 1.3	144	2.714
1.9	13.6 ± 1.4	146	2.718
2.0	14.4 ± 1.4	148	2.717
2.06	14.8 ± 1.4	149	2.717
2.1	15.1 ± 1.4	149	2.717
2.2	15.3 ± 1.5	151	2.716

the residual radial velocities for the 149 stars (excluding the high velocity star V CrB) with $|R - R_\circ| \leq 2.0\,\mathrm{kpc}$. These were then analyzed for the velocity dispersions α, towards the galactic centre, β, at right angles to this and in the galactic plane, and γ perpendicular to the galactic plane. Since the stars involved are primarily at low galactic latitude the value of γ is effectively indeterminate from our data. Thus in group 2, 30 percent of the weight of γ is in one star which happens to have a moderately large velocity residual making both the derived γ and its standard error uncertain. In group 1, the square of γ (the quantity actually determined) is negative, though not significantly so. We therefore adopt $\gamma = 12\,\mathrm{km\,s^{-1}}$, a value appropriate for the values of α and β found (e.g. Nordström et al. 2004). The value adopted will not affect our results in any significant way. The dispersions were calculated for all the stars in the annulus chosen and for the same stars divided into three groups by period (Group 1, $P < 470$ days, Group 2, $470 < P < 570$ days, Group 3 $P > 570$ days). Table 3 contains the results. It gives the values of α and β and the value of α derived on the assumption that $\beta = 0.63\alpha$. This is the ratio found in the extensive discussion of local F and G type dwarfs by Nordström et al. (2004). We use these latter values of α in the following. The discussion of the uncertainties in the adopted radial velocities in Paper II indicates that any contribution of observational scatter to the calculated dispersions will be small. Any such correction would slightly decrease the ages we calculate below.

Nordström et al. (2004) (their fig. 31) show the relation between their $\log \sigma_U$ (equivalent to $\log \alpha$) and log Age. The numerical values used for this figure were kindly provided to us by Dr Holmberg. Fitting a straight line to these (log - log) data we estimate the ages of the various groups in Table 3 together with their uncertainties. Using the tabulation of the Padova models (Girardi et al. 2000) which were also used by Nordström et al., we then estimate the mean initial masses of the various groups assuming solar metallicity. These results are given in Table 4. The errors correspond to the standard errors of α and do not take into account other sources of uncertainty (e.g. of the Padova models).

The ages derived are similar to those derived by Nishida

Table 3. Velocity Dispersions

Group	All	1	2	3	
N	149	49	50	50	
$\log P$	2.717	2.572	2.717	2.816	
α	26 ± 3	35 ± 4	21 ± 5	22 ± 3	$\mathrm{km\,s^{-1}}$
β	18 ± 3	19 ± 6	17 ± 5	17 ± 3	$\mathrm{km\,s^{-1}}$
γ	17 ± 12	–	50 ± 11	23 ± 11	$\mathrm{km\,s^{-1}}$
α	26 ± 3	34 ± 4	22 ± 5	22 ± 3	$\mathrm{km\,s^{-1}}$
β	18 ± 3	18 ± 6	19 ± 4	17 ± 3	$\mathrm{km\,s^{-1}}$
γ	12 (fixed)				$\mathrm{km\,s^{-1}}$
α	27 ± 2	32 ± 3	24 ± 3	24 ± 2	$\mathrm{km\,s^{-1}}$
β	$\beta = 0.63\alpha$				$\mathrm{km\,s^{-1}}$
γ	12 (fixed)				$\mathrm{km\,s^{-1}}$

Table 4. Estimated Ages and Masses

Group	$\log P$	α $\mathrm{km\,s^{-1}}$	Age Gyr	$M_{\rm init}/M_\odot$
All	2.717	27 ± 2	1.8 ± 0.4	1.8 ± 0.2
1	2.572	32 ± 3	3.1 ± 0.9	1.5 ± 0.2
2	2.717	24 ± 3	1.3 ± 0.5	2.1 ± 0.3
3	2.816	24 ± 2	1.3 ± 0.3	2.1 ± 0.2

et al. (2000) for C-Miras in Magellanic Cloud clusters. They adopt ages of $1.6 \pm 0.4, 1.7 \pm 1.0$ and 2.0 ± 0.2 Gyr for their three clusters in which the Miras have periods of 526, 450 and 491 days. Note that the main-sequence turn-off (TO) masses they adopt ($1.6 M_\odot$) are similar to the ones we would derive, e.g. the Girardi et al. TO mass is $1.4\,M_\odot$ for solar metallicity stars of age 2 Gyr (the initial masses of stars at the AGB tip at this age is larger, as shown in Table 4). van Loon et al. (2003) classify LI-LMC 1813 in the cluster KMHK 1603 as a C-Mira with a period of ∼680 days and suggest an age of 0.9-1.0 Gyr and $M_{\rm ZAMS}$ of 2.2 $M_\odot$ for it. This is consistent with our results. Somewhat smaller initial masses ($1.3\,M_\odot$) for dust-enshrouded AGB variables (both oxygen- and carbon-rich) were estimated by Olivier et al. (2001) from scale height considerations.

A new set of isochrones has been published by Pietrinferni et al. (2004). These differ significantly from those of Girardi et al. (2000) in the age range of concern for us (see Pietrinferni et al. section 6 and fig. 8). A Girardi solar-composition isochrone for 1.8 Gyr is best fitted with a Pietrinferni isochrone of age 2.5 Gyr. The TO masses are about 0.4 $M_\odot$ greater in the Pietrinferni et al. models. The difference between the two sets of isochrones is attributed by Pietrinferni et al. partly to differences in model input physics and partly to the interplay of the overshooting treatment with the input physics. It is clear from this that the absolute ages of our stars (and of Magellanic Cloud clusters with C-Miras) is still uncertain at the ∼ 0.5 Gyr level.

The results in Table 4 show that the shortest period stars (Group 1) are older and of smaller initial mass than the longest period ones. Groups 2 and 3 appear to have the same mean ages and masses. However, given the uncertainties one cannot rule out the possibility that a trend of age with period continues through the whole sequence of periods. In any case the results indicate that in the mean the

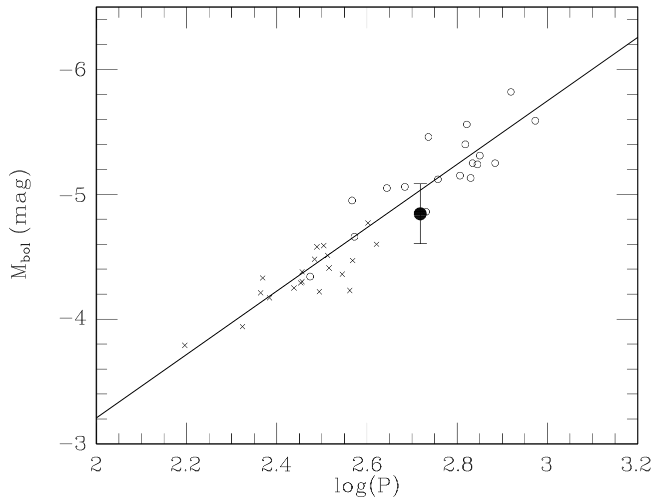

Figure 2. The M_{bol} versus $\log P$ relation for C-Miras. Crosses and open circles are for LMC stars (modulus 18.50) (see Paper I). The filled circle and error bar are for the present Galactic result.

stars of groups 2 and 3 are not the evolutionary products of group 1 stars. Similar conclusions apply to the O-Miras (see e.g. Feast & Whitelock 2000a). The relation between the O- and C-Miras is discussed in section 4.

The above discussion is based on the smooth variation of velocity dispersion with age which Nordström et al. (2004) deduce from their data. However, Quillen & Garnett (2000, 2001) derived the motions of stars in the Edvardsson et al. (1993) metallicity study of local F and G dwarfs and suggested that the velocity dispersions were constant in the age range 3 to 9 Gyr (see also Freeman & Bland-Hawthorn 2002). If this is so the age of our group 1 (the shortest period group) could be near 3 Gyr but could also be much older. In the latter case, there would be a rapid change of age with period. A comparison of the mean data points used by Quillen & Garnett with those used by Nordström et al. shows that there is no very strong disagreement between them. However, the relatively smooth variation of asymmetric drift and velocity dispersions with period for the O-Miras (Feast & Whitelock 2000a) may be difficult to understand if one adopts the conclusions of Quillen & Garnett (see section 4). Also the results of Binney et al. (2000) on the motions of main sequence and subgiant stars from the Hipparcos catalogue are consistent with a smooth variation of velocity dispersion with age such as that found by Nordström et al. It should, however, be stressed that whether one adopts the conclusions of Nordström et al. or those of Quillen & Garnett, our results suggest a dependence of C-Mira period on age at least at the short period end of the sequence.

4 THE O- AND C-MIRAS AND METALLICITY

In this section we discuss the relationship of the O-Miras to the C-Miras.

The ratio of carbon stars to late type oxygen-rich stars (M types) has been used by a number of workers as a measure of the mean metallicity of a galaxy, carbon stars being more frequent in low metallicity systems. A calibration of

Table 5. The Velocity Dispersion of O-Miras

FW Group	α km s^{-1}	P days	log P	N
2	76 ± 8	175	2.243	17
3	69 ± 6	228	2.358	24
4	46 ± 4	272	2.435	26
5	50 ± 4	324	2.511	40
6	45 ± 4	383	2.583	32
7	28 ± 4	453	2.656	15

this relation has recently been obtained by Battinelli & Demers (2005) from local group galaxies.

However, at least in the case of Mira variables, this ratio must also be affected by the age distribution of the populations studied. Both the asymmetric drift and the velocity dispersion of O-Miras are a function of period (e.g. Feast 1963, Feast & Whitelock 2000a). Table 5 shows the velocity dispersion, α, for O-Miras as a function of period using the data on their space motions given by Feast & Whitelock. To be compatible with the C-Mira results we have taken a mean of $\Sigma_{V_R}(\equiv \alpha)$ and $1.59\Sigma_{V_\theta}(\equiv \beta/0.63)$. Taken together with the occurrence of short period Miras in globular clusters (e.g. Feast et al. 2002) this indicates ages ranging from that of metal-rich globular clusters at the short period end to $\sim$ 2 Gyr at $\sim$ 450 days and probably younger for the longer period (OH/IR) Miras. The last column of Table 5 shows the number of stars in each of the period groups. A comparison with Table 4 shows that the optically selected sample of O-Miras discussed by Feast & Whitelock are, at least in the main, a much hotter and older population than the C-Miras discussed above [2].

As an example of the effect of age on the ratio of O- to C-Miras one can consider the solar neighbourhood. In an approximately distance-limited sample of optically selected Miras in the solar neighbourhood Wood & Cahn (1977) estimated there were about 14 times more O-Miras than C-Miras. Optical samples are weighted to the shorter period (older) stars. On the other hand, in the case of the longer period (younger) dust enshrouded stars a distance limited sample shows roughly equal numbers of O- and C-Miras (e.g. Olivier et al. 2001, fig. 16) [3]. Clearly the ratio of O- to C-Miras in a given population must be at least partly dependent on age. Since the younger stars are unlikely to be metal-weak compared with the older ones (note the period-metallicity relation for O-Miras (e.g Feast & Whitelock 2000b), the above result is not consistent with a simple decrease in the O-Mira to C-Mira ratio with decreasing metallicity.

The above two paragraphs indicate that the ratio of C-Miras to O-Miras in a population will depend on the age distribution in that population. That other factors can affect this ratio is shown by the galactic Bulge. The Bulge contains many M-type giants and O-Miras with a wide range of periods, up to 700 days in the SgrI window (Glass et al. 1995) and even longer near the galactic centre (Wood et al. 1998). In contrast there is an absence of C-Miras and normal carbon stars in general from the Bulge [4]. In the past this was frequently assumed to be a metallicity effect (e.g. King 1993) with the Bulge being super-metal rich compared to the solar neighbourhood. However, it is now known that the Bulge and the local disc population have rather similar metallicities. Rich & Origlia (2005) find a mean $[Fe/H] = -0.19$ for Bulge M-type giants and Fullbright et al. (2005) obtained a mean $[Fe/H] = -0.10$ for Bulge K giants (see also McWilliam & Rich 2003). These values have to be compared with a mean thin disc metallicity of $[Fe/H] = -0.14$ (Nordström et al. 2004). There have in fact been suggestions (Haywood 2001, 2002, Taylor & Croxall 2005) that the mean metallicity of the local thin disc could be even greater than this ($[Fe/H] \sim -0.04$).

Our local sample of C-Miras has (Table 4) the same kinematics as the longer period local O-Miras (e.g. Group 7 of Table 5). These local subgroups of O- and C-Miras are thus presumably of the same age. The presence in the Bulge of O-Miras in the Group 7 period range and the absence of C-Miras cannot therefore be ascribed to age difference nor, in view of the above discussion to different overall metallicities of their parent populations [5].

However, there is a difference between the Bulge and the local populations which seems to explain this situation. It was found by Glass et al. (1995) that the JHK colours of Bulge O-Miras were different from those in the LMC. This was explained (Feast 1996, Feast & Whitelock 2000b) as due to stronger H_2O bands at a given period in the Bulge stars. A rough estimate showed that this could be accounted for by a difference in oxygen abundance between the two parent populations of a factor of about 2.5 (0.4 dex). It is now known from spectroscopic work that oxygen (an α element) is enhanced in Bulge stars. Rich & Origlia (2005) find [O/Fe] $\sim +0.3$ in Bulge M-giants (see their fig. 5). On the other hand [O/Fe] tends to be lower in the LMC than in the solar neighbourhood except for very metal-poor objects (Hill 2004, Cole et al. 2005). It therefore seems a reasonable assumption that this oxygen overabundance in the Bulge is sufficient to keep $O/C > 1.0$ through the dredge-up phases of Bulge giants and thus to prevent the occurrence of carbon stars. It is worth noting that the evolutionary tracks of Salasnich et al. (2000) suggest that at the intermediate ages of the C-Miras and the longer period O-Miras, an α element enhancement will not significantly affect the age/mass relation.

[2] It is worth noting that if we adopt the velocity dispersion - age relation favoured by Quillen & Garnett (2000, 2001) the kinematics of the bulk of the optically selected local O-Miras would fall in the discontinuity in their relation, between their thin and thick disc components. There would thus be no local dwarf stars with similar kinematics as counterparts to these O-Miras, a surprising result. This problem is not evident if the Nordström et al. relation is adopted.

[3] At the very long period end of the distribution, $P > 1000$ days, there are (OH/IR) O-Miras both in the solar neighbourhood (Olivier et al. 2001 fig. 3) and also in the LMC (Whitelock et al. 2000) but few, if any, C-Miras. IRAS 01144+6658 is a possible exception (See section 6).

[4] The C-Mira IRAS 17463–4007 with $\ell = 350^\circ.8$, $b = -6^\circ.5$ and $d = 10.6$ kpc (see paper II) might lie within or near the Bulge.

[5] As has long been known, the range of O-Mira periods in the Bulge implies a range of ages, despite the conclusion of Zoccali et al. (2003) from colour-magnitude diagrams that most of the Bulge is very old.

In the light of the discussion in this section we can expect the ratio of O- to C-Miras (and probably the relative frequency of carbon to oxygen rich giants generally) in different systems to be a function of overall metallicity, age and detailed abundance ratios such as [O/Fe]. Thus the correlation between overall metallicity and the ratio of carbon-rich to oxygen-rich giants in local group galaxies (e.g. Battinelli & Demers 2005) is of particular interest since it would seem to imply other underlying correlations (i.e. between age, overall metallicity and detailed abundance ratios).

The galactic C-Miras belong kinematically to the thin disc and the bulk of the thin disc stars, including those of the relevant ages, have only slight metal deficiencies. As just noted, Nordström et al. (2004) estimate an overall mean value of [Fe/H] = –0.14 with a dispersion of 0.19. If the production of C-Miras were strongly dependent on metallicity, this would skew the mean abundance of these stars to lower than that of the general thin disc. In fact Abia et al. (2001) give spectroscopic estimates near solar for two of them (V Oph with [M/H] = 0.0 and VX Gem with [M/H] = –0.15) and for Galactic carbon stars in general they find near solar metallicities.

Abundance determinations for C-Miras are difficult but a spectroscopic study of a large sample might show whether there is any bias in their metallicity distribution compared with old disc stars of the same age.

5 STARS WITH HIGH VELOCITIES

It has been known for many years that the C-Mira V CrB has a high velocity perpendicular to the galactic plane (e.g. Eggen 1969). Using the radial velocity in Paper II table 4, the Hipparcos proper motion components and a PL distance, the velocity components relative to the local standard of rest are $u = +28$, $v = -67$ and $w = -92\,\mathrm{km\,s^{-1}}$. It also seems to be underabundant in metals. Abia et al. (2001) give [M/H] = –1.35. Kipper (1998) gave [Fe/H] = –2.12. The large difference is no doubt partly due to the problems of spectroscopic analysis of such a cool star. Nevertheless, it seems safe to assume that it has an unusually low metallicity for a galactic C-Mira. It seems most likely to be an extragalactic interloper. There are C stars in the region of the galactic halo which are likely to have an extragalactic origin (e.g. Ibata et al. 2001) and at least in the Sgr dwarf galaxy some of these are known to be Miras (Whitelock et al. 1999).

V CrB is the only star which we have omitted from the discussions of the earlier sections. However, for completeness we list in Table 6 the stars which have residuals from the galactic rotation solutions of greater than $|50|\,\mathrm{km\,s^{-1}}$. The table is in two sections with stars in the $|R_o - R| < 2.0\,\mathrm{kpc}$ annulus separated from those outside. In view of the velocity dispersions involved it is not surprising that there are a few stars with relatively large residuals, and outside the annulus there may well be significant deviations from the model adopted. It is however somewhat intriguing that in the table there are four stars in the general direction of the galactic anticentre and one in the general direction of the galactic centre where the effects of the model are less significant. These stars (ZZ Gem, AZ Aur, IRAS06088+1909, RT Gem, IRAS 17222–2328) all have a large radial component outwards from the galactic centre. It would be interesting to study their space motions and to see whether this is anything more than a statistical chance effect. A somewhat more complex outward motion was found for short period O-Miras (Feast & Whitelock 2000a, Feast 2003a) which was attributed to a bar-like motion. It should however be noted that the kinematics show that the short period O-Miras and the C-Miras discussed in this paper belong to quite different populations.

6 DISCUSSION

In section 2 we found that if we assume the C-Miras follow a period, absolute bolometric magnitude relation of the same slope as for the C-Miras in the LMC, then the zero-point of this relation is, within the uncertainties, the same in the Galaxy as in the LMC despite possible differences in metallicities. This is a useful result since it suggests that C-Miras may be used with some confidence as distance indicators in populations of different metallicity. This is of importance for extragalactic applications. It may well be that in some applications (e.g. extragalactic work), it will be necessary to derive the apparent bolometric magnitudes from near infrared observations alone. In that case the bolometric corrections derived in Paper I should be valuable.

Our kinematic results indicate that the C-Miras, at least in the period ranges we cover, come from a rather restricted range of ages and initial masses. The low mean initial masses and intermediate ages we find are in agreement with those estimated for the Magellanic Cloud clusters containing C-Miras. They are also in agreement with the results of Kahane et al. (2000). These authors compared isotope abundances in the C-Mira CW Leo (IRC+10216) with theoretical predictions and found that for solar metallicities their $5\,M_\odot$ model disagreed with the observations but that models with masses less than about $3\,M_\odot$ were satisfactory.

Considerably higher initial masses have sometimes been suggested at least for the longer period C-Miras. Bergeat et al. (2002) suggest $\sim 4\,M_\odot$, whilst Raimondo et al. (2005) suggest that the bulk of the long period variables (in which they include non-Miras) in the SMC are of age ~ 0.3 to 0.5 Gyr, much younger than our estimated ages for C-Miras. Raimondo et al. suggest that the SMC variables were formed in a burst of star formation believed to have taken place at about that time (Harris & Zaritsky 2004). Our mean age, $\sim 2\,\mathrm{Gyr}$ (or the somewhat larger value suggested by the Pietrinferni et al. models), if it applies to the SMC C-Miras, would not be consistent with them being formed in such a burst. They would in fact be nearer in age to the burst that Harris & Zaritsky date at 2.5 Gyr ago.

It should be noted that whilst the $K - \log P$ diagram of Raimondo et al. (2005)(their fig. 8) shows the Wood "C" sequence (on which the C-Miras lie) in broad agreement with the PL(K) relation of Feast et al. (1989) shifted to the SMC distance, though much broader due to their dependence on single near IR observations, their $M_{bol} - \log P$ diagram (their fig. 15) has a Wood "C" sequence which is much steeper, and displaced from our PL(M_{bol}) relation. This may be connected with the bolometric corrections for carbon stars that they adopt from Bergeat et al. (2001, 2002).

Our results, considered together with those on the C-Miras in Magellanic Cloud clusters, suggest that the C-Miras

Table 6. Stars with High Residual Velocities

Star	ℓ	b	V_{lsr}	Residual	P
	(deg)		(km s^{-1})		(day)
$\lvert R_o - R\rvert < 2.0$kpc					
V CrB	63.27	+51.23	–102	–96	358
ZZ Gem	187.60	+5.54	+67	+62	316
KY Cam	140.93	+3.47	–88	–61	477
AZ Aur	172.30	+8.16	+71	+76	416
$\lvert R_o - R\rvert > 2.0$kpc					
IRAS 06088+1909	191.47	+0.27	+64	+54	493
RT Gem	195.73	+7.33	+101	+84	350
IRAS 16171–4759	334.86	+1.35	+40	+78	560
IRAS 17222–2328	2.13	+6.76	–61	–65	603

should provide a mean age for a population in which they occur (say in an extragalactic system). In addition the suggestion in our data that initial mass and age are a function of the period of these stars, at least at the shorter periods, indicates that a comparison of the distribution of C-Mira periods in different stellar systems will enable a comparative study of star formation in the interval ~ 1.5 to ~ 3.0 Gyr ago.

The analysis of radial velocities and photometry in this paper is based on the assumption that the bulk of galactic carbon Miras lie on a PL relation as do those in the LMC, including the ones in LMC clusters discussed above. LMC work (e.g. Whitelock et al. 2003) also shows that there are a small number of large amplitude AGB variables which lie above the PL relation. Providing such stars are also rare in our Galaxy they should not significantly affect any of our conclusions. It has been suggested (Whitelock & Feast 2000, Whitelock et al. 2003) that these rare overluminous stars are undergoing Hot Bottom Burning (HBB) - although this is controversial in the case of C-rich stars as HBB is expected to convert the carbon to nitrogen. Theory (e.g. Sackmann & Boothroyd 1992) then suggests that these stars probably have masses in excess of $4M_\odot$, significantly greater than those of normal Miras in the same period range. It is therefore of interest that one such star discussed by Whitelock et al., IRAS 04496–6958, is possibly a member of the small cluster HS33. Van Loon et al. (2005) obtained a colour-magnitude diagram of this cluster. Whilst separation of the cluster from the field stars is difficult they suggest an age in the range 110 to 200 Myr and hence a relatively massive progenitor for IRAS 04496–6958 in qualitative agreement with HBB predictions.

There is a suggestion from the velocity dispersions that at a given period the C-Miras are younger than the O-Miras. The period-luminosity relation for C-Miras (Whitelock et al. 2005) and that for O-Miras (Feast et al. 1989) suggest that also, at a given period, the C-Miras are fainter bolometrically than the O-Miras, although the thin-shelled members of these two classes obey the same PL(K) relation. Caution is required in interpreting this since the spectral energy distribution is different in the two types of Miras and may lead to different systematic errors in deriving the bolometric magnitudes. For instance thin-shelled O-Miras whose energy distributions peak in the near infrared may have estimated bolometric magnitudes which are one or two tenths of a magnitude too bright because the $JHKL$ filters avoid the main stellar water absorption bands (Robertson & Feast 1981). Whilst accurate bolometric magnitudes are needed for comparison with theoretical predictions, possible systematic errors of this type are not important in using Miras as distance indicators as long as the bolometric luminosities are calculated in a consistent manner. If despite the above caveat, there is a real difference in the bolometric luminosities of O- and C-Miras of the same age, this would be difficult to understand unless, for instance, the two groups had different overall metallicities. In that case, objects in one group (presumably that of lower metallicity) may have become carbon stars before, or immediately on, entering the Mira stage. The work of Abia et al. (2001) discussed at the end of our section 4, nevertheless, suggests that carbon stars in the local galactic disc have metallicities close to that of the disc mean, though a fuller understanding of the metallicities of disc O- and C-Miras is very desirable.

It is striking that in the work on obscured Miras in the Magellanic Clouds (Whitelock et al. 2003) there are no C-Miras with periods greater than 1000 days. The longest period C-Mira in our galactic sample is 815 days and there is an object with a possible period of 1060 days in the sample of C-Miras discussed by Groenewegen et al. (1998). However, the details of this star have not, so far as we know, been published. We have therefore not included it in the present discussion. On the other hand the LMC sample of Whitelock et al. contains a group of O-Miras with periods in the range 1097 to 1393 days. The absence of such long period O-Miras in the galactic Bulge, except in the central region (Glass et al. 1995, Wood et al. 1998), suggests that they are too young to be there. They may well be younger than the longest period C-Mira. If that is the case they may be relatively massive objects which have been prevented from becoming C-Miras by Hot Bottom Burning (Boothroyd et al. 1993).

ACKNOWLEDGMENTS

We thank the referee, Jacco van Loon, for his comments.

REFERENCES

Abia C. et al., 2001, ApJ, 559, 1117
Battinelli P., Demers S., 2005, A&A, 434, 657
Bergeat J., Knapik A., Rutily B., 2001, A&A, 369, 178
Bergeat J., Knapik A., Rutily B., 2002, A&A, 390, 967
Binney J., Dehnen W., Bertelli G., 2000, MNRAS, 318, 658
Boothroyd A. I., Sackmann I. -J., Ahern S. C., 1993, ApJ, 416, 762
Claussen M.J., Kleinmann S.G., Joyce R.R., Jura M., 1987, ApJS, 65, 385
Cole A.A., Tolstoy E., Gallagher J.S., Smecker-Hane T.A., 2005, AJ, 129, 1465
Eggen O.J., 1969, PASP, 81, 346
Eisenhauer F. et al. 2005, ApJ, 628, 246
Feast M.W., 1963, MNRAS, 125, 367
Feast M.W., 2000, MNRAS, 313, 596
Feast M.W., 2002, MNRAS, 337, 1035
Feast M.W., 2003a, in Nakada Y., Honma M., Seki M., eds., Mass -Losing Pulsating Stars and their Circumstellar Matter, Kluwer, Dordrecht, p83
Feast M.W., 2003b, in Alloin D., Gieren W., Stellar Candles for the Extragalactic Distance Scale, Springer, Berlin, p45
Feast M.W., Glass I.S., Whitelock P.A., Catchpole R.M., 1989. MNRAS, 241, 375
Feast M.W., Whitelock P.A., 1997, MNRAS, 291, 683
Feast M.W., Whitelock P.A., 2000a, MNRAS, 317, 460
Feast M.W., Whitelock P.A., 2000b, in Matteucci, F., Giovannelli F., eds. The Evolution of the Milky Way, Kluwer, Dordrecht, 229
Feast M.W., Whitelock P.A., Menzies J.W., 2002, MNRAS, 329, L7
Freeman K., Bland-Hawthorn, J., 2002 ARAA, 40, 487
Fullbright J.P., McWilliam A., Rich R.M., 2005, ApJ, in press, (astro-ph/0510408)
Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, A&AS, 141, 371
Glass I.S., Whitelock P.A., Catchpole R.M., Feast M.W., 1995, MNRAS, 273, 383
Groenewegen M.A.T., van den Hoek L.B., de Jong T., 1995, A&A, 293, 381
Groenewegen M.A.T., Whitelock P.A., 1996, MNRAS, 281, 1347
Groenewegen M.A.T., Whitelock P.A., Smith C.H., Kerschbaum F., 1998, MNRAS, 293, 18
Harris J., Zaritsky D., 2004, ApJ, 127, 1531
Haywood M., 2001, MNRAS, 325, 1365
Haywood M., 2002, MNRAS, 337, 151
Hill V., 2004, in McWilliam A., Rauch M., Origin and Evolution of the Elements Cambridge University Press, p203
Ibata R., Lewis G. F., Irwin M., Totten E., Quinn T., 2001, ApJ, 551, 294
Kahane C., Dufour E., Busso M., Gallino R., Lugaro M., Forestini M., Straniero O., 2000, A&A, 357, 669
King I.R., 1993, in Dejonghe H., Habing H., Galactic Bulges (IAU Symp. 153), Kluwer, Dordrecht, p3
Kipper T., 1998, Baltic Ast., 7, 435
Matsuura M.et al., 2005, A&A, 434, 691
McWilliam A., Rich R.M., 2003, astro-ph/0312628
Menzies J.W., Feast M.W., Whitelock P.A., 2006, MNRAS, submitted (Paper II)
Nishida S. et al., 2000, MNRAS, 313, 136
Nordström B. et al., 2004, A&A, 418, 989
Olivier E.A., Whitelock P.A., Marang F., 2001, MNRAS, 326, 490
Pietrinferni A., Cassisi S., Salaris M., Castelli F., 2004, ApJ, 612, 168
Pont F., Mayor M., Burki G., 1994, A&A, 285, 415
Quillen A.C., Garnett D.R., 2000, astro-ph/0004210
Quillen A.C., Garnett D.R., 2001, in Funes J.G., Corsini E.M., Galaxy Disks and Disk Galaxies, ASP Conf. Ser. 230,p 87
Raimondo G., Cioni M-R. L., Rejkuba M., Silva D.R., 2005, A&A, 438, 521
Rich R.M., Origlia L., 2005, ApJ, 634, 1293
Robertson B.S.C., Feast M.W., 1981, MNRAS, 196, 111
Salasnich B., Giradi L., Weiss A., Chiosi C., 2000, A&A, 361, 1023
Taylor B.J., Croxall K., 2005, MNRAS, 357, 967
van Loon J.Th., Marshall J.R., Matsuura M., Zijlstra A.A., 2003, MNRAS, 341, 1205
van Loon J.Th., Marshall J.R., Zijlstra A.A., 2005, A&A, 442, 597
Whitelock P.A., Feast M.W., 2000, Mem. Soc. Astron. Ital., 71, 601
Whitelock P.A., Feast M.W., van Loon J. Th., Zijlstra A.A., 2003, MNRAS, 342, 86
Whitelock P.A., Menzies J.W., Irwin M., Feast M.W., 1999 in Whitelock P.A., Cannon R., The Stellar Content of Local Group Galaxies (IAU Symp. 192) Ast. Soc. Pacif. p136
Whitelock P.A., Feast M.W., 2000, MNRAS, 319, 759
Whitelock P.A., Feast M.W., Marang F., Groenewegen M.A.T., 2006, MNRAS, submitted (Paper I)
Wood P.R. et al. 1999, in Le Bertre T., Lèbre A., Waelkens C., Asymptotic Giant Branch Stars, IAU Symp. 191, Ast.Soc. Pac. p151
Wood P.R., Cahn J.H., 1977, ApJ, 211, 499
Wood P.R., Habing H.J., McGregor P.J., 1998, A&A, 336, 941
Zoccali M. et al., 2003, A&A, 399, 931